An Antenna Concept Integrated with Future Solar Sails

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1. Introduction and Statement of Problem

Inflatable solar sails have been proposed, [1], which enable planetary missions employing solar power flux to provide thrust for the spacecraft thus decreasing the required additional propellant (Fig. 1). To maximize the capture of solar flux, solar sails are required to have a large surface area (i.e. 100 m in diameters, see [1]). The question has been raised if one can envision an antenna concept that can be readily integrated into the solar sail itself. Assuming that the inner portion of the sail has an acceptable level of flatness, one may then seek for concepts that provide required antenna gain. Applications of zone plate Fresnel antennas can be envisioned in solar sails (Fig. 2). The Zone plate (Fresnel) antenna is a type of reflector antenna in which strips of reflecting/nonreflecting materials are arranged on a flat surface to maximize the directivity of the plate (see Fig. 1). Having a lesser gain compared to parabolic antennas, they may be used in place of parabolic antennas where geometry may dictate a non-parabolic reflector surface. These sails can have a variety of shapes; however, for the purpose of this discussion, we focus on flat sails although most of the analysis can be easily extended to non-flat shapes and will be discussed as appropriate. Our intent in this paper is to propose a comparable and alternative means of antenna design for Deep Space communication by taking advantage of solar sails of large surface area and by incorporating zone plate Fresnel antennas on the sail.

In addition, for the purpose of developing clear insight into the preformance of the antenna and to avoid unnecessary added complexity in the analysis, we propose a 2-D MoM and PO analysis of the geometry in order to assess the computational accuracy of PO for the 3-D structures.

2. Comparative Study

This comparative study will be based on the performance of a 4-m parabolic antenna (operated at 8.41 GHz) used aboard the Cassini spacecraft versus that of a 10-m flat portion of a solar sail designed as a Fresnel antenna. Analysis in this paper is carried using Physical Optics (PO) which has also been verified using Method of Moments (MoM) [2]. A summary of analysis is presented in Table 1, which we will refer to it frequently as we present the results. The feed geometry consists of four uniformly excited array elements (about 0.41 λ apart) producing a nearly 10 dB feed taper over the reflector geometry with F/D=1. The 4-m parabolic reflector and the corresponding 4-m Fresnel antenna geometry are displayed in Figures 3 (a), and (b). The Fresnel antenna is designed as a series of alternatively spaced panels whose lengths and spacing are determined based on examining PO current on a 4-m continuous flat panel. To better describe the design philosophy, Fig. 4 displays phase behavior of PO current for a 4-m continuous panel illuminated by the same feed. The zone plate reflector is then designed by masking off portions of the plate where the PO current phase is negative thereby eliminating the undesired cancellation in PO integration due to phase reversal. Consequently, the 4-m flat panel (having nearly the same directivity as that of the feed, 10.58 dB) that merely reflects the incident field of feed, is changed to a flat reflector of 19.24 dB gain (see Table 1). To verify the results using PO analysis, a comparison is made between PO and MoM for the Fresnel antenna (Fig. 3(c)), which displays excellent agreement between the methods despite MoM anticipated edge current behavior on the Fresnel antenna. Fig. 3(d) displays a comparison between the patterns of 4-m parabolic and the 4-m Fresnel antennas. Note that although we have achieved a high gain pattern with the Fresnel antenna, the sidelobes are substantially higher for the 4-m Fresnel antenna compared to the 4-m parabolic one. Similarly, to take advantage of large surface area of solar sails, we can design a 10-m flat Fresnel antenna with a back plane to achieve a gain of 28.50 dB, the same as that of the 4-m parabolic antenna (see Table 1). The Fresnel reflector has 65 reflecting elements ranging from 25.7 λ to 0.7 λ in length and spacing between 8 λ and 1.1 λ.

Random surface errors on the solar sails will also reduce antenna gain. The effect of the surface error is considered here for both the 4-m and 10-m Fresnel antennas without the back plane. This is achieved by moving the reflecting elements back and forth based on a random deviation not to exceed a specified peak error (i.e $\lambda/10$, $\lambda/20$, and $\lambda/30$.) A number of samples (100 samples for each case) of randomly generated Fresnel reflectors with surface errors were analyzed and gain for each case was computed. For a given rms surface error, it was found that the gains of both 4-m and 10-m Fresnel reflectors decrease in the same order, supporting the argument in [3] that gain loss is a function of reflector F/D, and (rms surface error)/λ. Gain losses for peak errors of $\lambda/10$, $\lambda/20$, and $\lambda/30$ were respectively estimated at 2.1, 0.51 and 0.19 dB as compare to the structure without any surface error for the 10-m Fresnel antennas.

Finally, the average power patterns for the 10-m Fresnel antenna with and without surface random errors are shown in Fig. 5. The patterns display reduction of peak power as well as sidelobe degradation as higher random surface error is introduced on the reflector surface. In addition, as a result of power averaging of a large number of random samples, nulls in the patterns have started to be filled as discussed in [3] (see $\lambda/10$ peak surface error case in Fig. 5).

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Table 1: Performance comparison among different reflector configuration (2-D & 3-D)

Reflector Geometry, f = 8.41 GHz (λ = 0.03567819 m), 10 dB Feed Taper, F/D =1						
	Computed 2-D Gain/Gain Loss				Estimated 3-D Gain	
Geometry	Gain of 4 m (dB)	Gain Loss for 4 m	Gain of 10 m (dB)	Gain Loss for 10 m	4-m (dB)	10-m (dB)
Parabolic Reflector (Reference Geometry)	**28.05**	0.00	**32.00**	0.00	50.08	57.98
Gain ~ 2π L/λ	28.48	0.43	32.46	0.46	50.93	58.89
Flat Plate	10.58	-17.47	10.52	-21.48	15.14	15.02
Zone Plate Antenna with $\lambda/4$ back plane (0-180 DEG)	24.10	-3.95	28.50	-3.50	42.18	50.98
Zone Plate Antenna w/o back plane (0-180 DEG)	19.24	-8.81	23.18	-8.82	32.46	40.34
Zone Plate Antenna w/o back plane & Avg. of 100 Samples (0-180 DEG) &						
+/- $\lambda/30$ Peak random surface error	19.09	-8.96	22.99	-9.01	32.16	39.96
+/- $\lambda/20$ Peak random surface error	18.84	-9.21	22.67	-9.33	31.66	39.32
+/- $\lambda/10$ Peak random surface error	17.53	-10.52	21.08	-10.92	29.04	36.14

Reference:

[1] R. H. Frisbee, and J. H. Brophy, "Inflatable Solar Sails for Low-Cost Robotic Mars Missions," pp. 1-10, AIAA 97-2762, 33rd AIAA/ASME/ASEE Joint Propulsion Conference & Exhibit, July 6-9, 1997, Seattle, WA

[2] Behrouz Khayatian, Yahya Rahmat-Samii, " __ ", Journal of Electromagnetic Waves and Applications, Vol. 14, No. 7, pp. 1001-1031, 2000

[3] Yahya Rahmat-Samii, " __", IEEE Transactions on Antennas and Propagation, Vol. AP-31, No. 1, Jan. 1983, pp. 92-98.

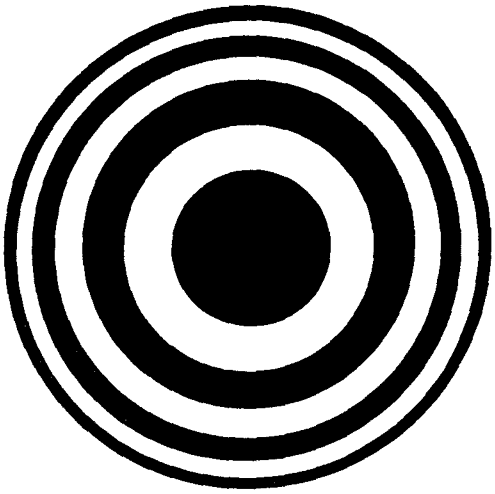

Figure 2: Zone plate (Fresnel) antenna with rings of conducting/non-conducting elements.

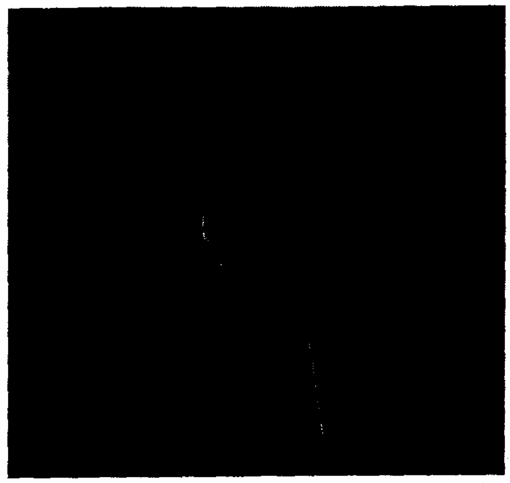

Figure 1: A futuristic view of a solar sail taken from NASA web site at http://antwrp.gsfc.nasa.gov/apod/ap000526.html

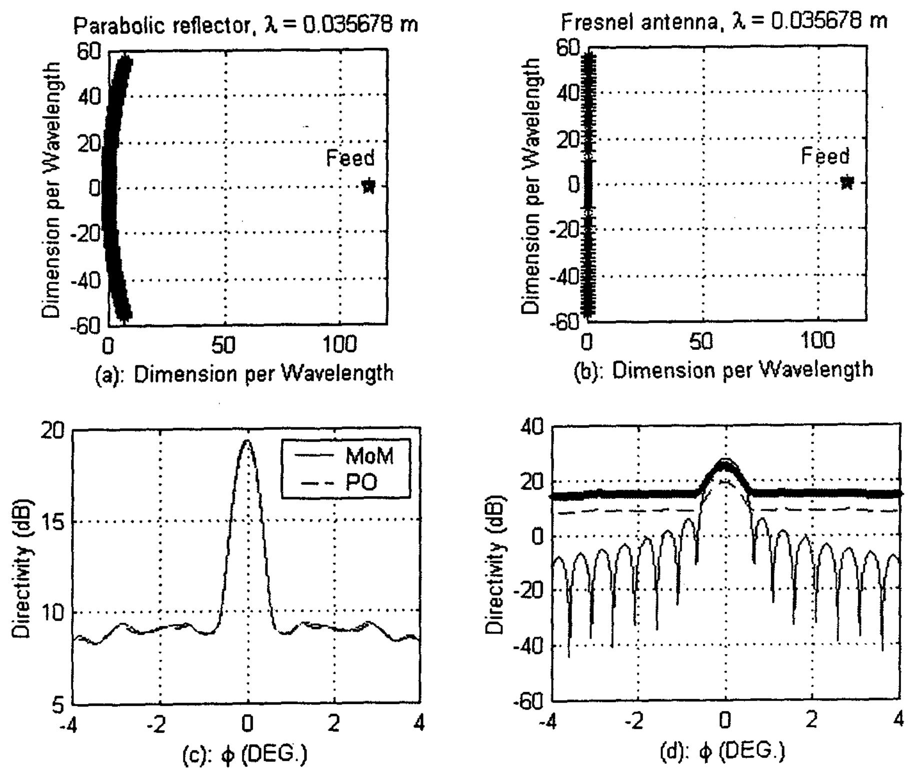

Figure 3: (a) 4-m parabolic reflector with 10 dB feed taper, (b) 4-m zone plate Fresnel antenna without back plane, (c) comparing results of MoM and PO analysis on the 4-m Fresnel antenna, (d) pattern comparison among (4-m Parabolic: solid/blue line; 4-m Fresnel antenna without back plane: dashed/green line; 4-m Fresnel antenna with λ/4 backplane: dotted/red line).

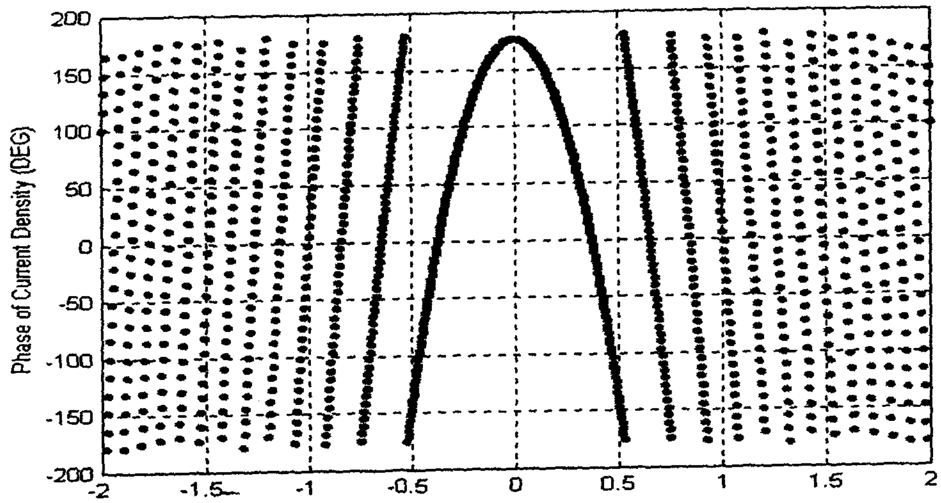

Figure 4: Phase distribution along a continuous flat 4-m reflecting plate. To design the Fresnel antenna, only portions of the plate where phase is ranging from 0 to 180 degrees are retained as the reflecting elements (i.e. from –0.37 to 0.37, …). The other portions of the plate will be masked off with a non-reflecting material (i.e. from 0.37 to 0.54, …)

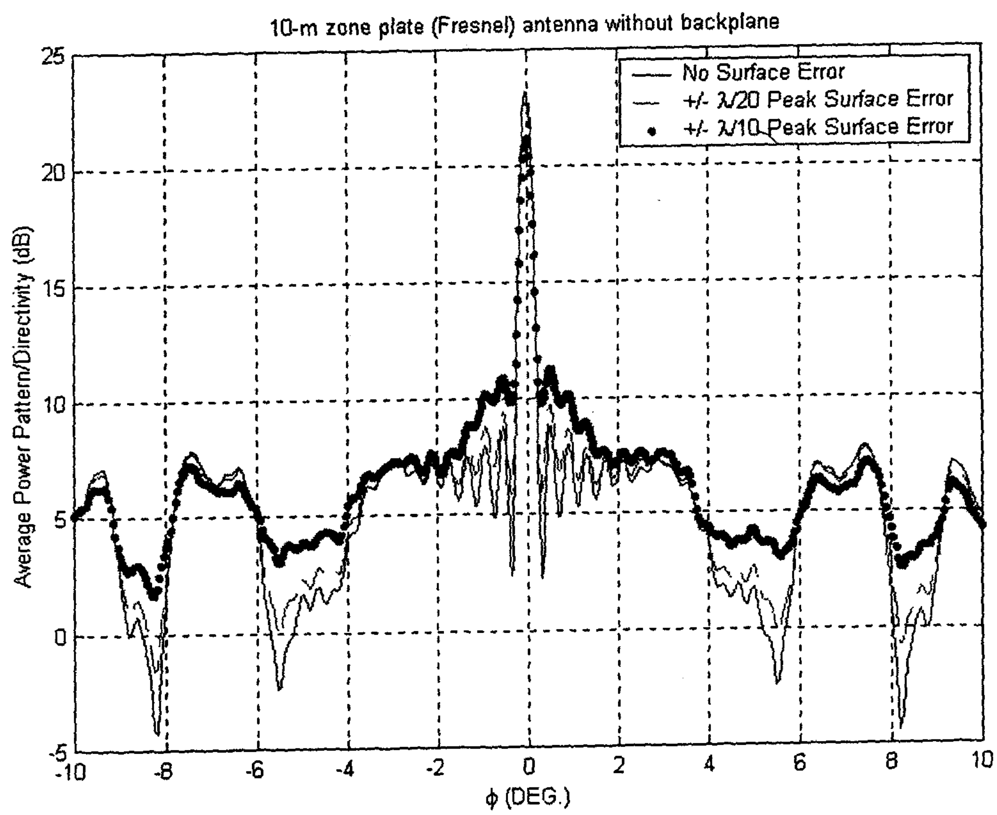

Figure 5: Comparison of average power pattern with and without random surface error for 10-m Fresnel antenna. As random surface error increases, gain reduces, sidelobe structure degrades and nulls in the pattern get filled.